

de vibration (et par conséquent la hauteur du son) doit baisser. Cette manipulation permet de dévier des sons de l'échelle harmonique naturelle. Les compositeurs classiques et romantiques exploitèrent cette nouvelle possibilité afin d'avoir le chromatisme avec le cor naturel, tout en faisant usage du système ascendant (boucher complètement). Cette sonorité — passablement altérée ! — serait aujourd'hui considérée comme défectueuse et ne remplirait pas les exigences du concert. A l'époque, il n'y avait pas d'autres solutions pour extraire les sons intermédiaires. Un exemple : dans *Fidelio* de Beethoven, les passages de cor dans l'air de Leonore (1er acte) comprennent 30 sons bouchés sur 70. Grâce à l'invention et à l'introduction des pistons (après 1820), le corniste d'aujourd'hui n'est plus obligé d'obtenir les sons intermédiaires en bouchant avec la main, mais il **corrige** son intonation. Il la corrige également avec la tension labiale.

5. Au sujet des problèmes d'intonation. La pureté d'intonation des cuivres reste incertaine pour deux raisons. D'abord, il faut savoir que l'orchestre ne pratique pas le compromis du système tempéré. L'oreille du musicien d'orchestre perçoit l'intonation harmonique. Le même son — c'est-à-dire noté au même endroit sur la portée — ne se trouve pas exactement à la même hauteur selon les tonalités ou les harmonies employées. De plus, le système des 3 pistons devient insuffisant lorsque les doigtés sont combinés. Le 1er piston baisse d'un ton entier, le 2e d'un demi ton et le 3e d'une tierce mineure. Le 1er plus le 2e piston combinés ne donnent pourtant pas exactement la tierce mineure. Le 2e plus le 3e pas exactement la tierce majeure. Le ton entier du degré situé entre la 8e et la 9e harmonique est — par rapport au nombre de vibrations — plus grand que celui situé entre la 9e et la 10e harmonique. Le corniste doit percevoir ces différences avec son oreille et corriger, soit avec la main, soit avec les lèvres, d'où la nécessité absolue de bénéficier d'une bonne ouïe et d'une bonne représentation intérieure des sons (afin d'anticiper l'écoute de ce qu'il va jouer).

Pour ceux qui se sentent attirés par ces problèmes, je ne peux que recommander le remarquable ouvrage scientifique de Martin Vogel, « *Die Intonation der Blechbläser* » (L'intonation chez les cuivres), volume I de la Collection Orpheus pour les questions fondamentales de la musique. (Publié en allemand seulement par la Gesellschaft zur Förderung der systematischen Musikwissenschaft, Düsseldorf, 1961.)

THE INNER ACOUSTICS OF THE HORN

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of the 7th International Congress on Acoustics,
Budapest 1971.

Since its introduction into the orchestra by Lully, around 1660, the horn has experienced two radical changes, both of which express themselves clearly in the musical use to which the horn was put.

First Epoch

Bach's and Handel's corno da caccia, today's hunting horn, was blown open, without the hand in the bell.

Second Epoch

Around 1750 the Dresden hornist, Josef Hampel, invented the stopping of the bell with the right hand. If the hand stops the opening of the bell only partially, the pitch goes down by as much as a whole tone or more. If the hand closes the opening completely, the tone jumps a half step upwards. On the basis of this multiplication of the possible notes, the horn was used liberally by the Classical composers Haydn, Mozart, and Beethoven, by the Romantics Weber and Schubert, and in the early periods of Wagner, Schumann, and Brahms, as well. This epoch has been called the Golden Age of the horn. Up until now, the variation in pitch caused by the right hand has not been able to be explained physically. Our experiments have brought the solution to the puzzle.

Third Epoch

After 1820, the valve, invented shortly before, was introduced, bringing to all brass instruments the possibility of producing the entire chromatic scale.

Acoustics, already a science during Greek antiquity, became highly developed from 1800 onwards, as is testified to by a rich collection of professional literature. The numerous theoretical and mathematical treatises, as well as the analogies from electricity, are generally incomprehensible to the man in the street. With our experiments, we tried to investigate the processes of vibration in the tubing of brass instruments, using simple constructions as a point of departure, and to present them to hornists and instrument makers in an understandable form.

Sound as perceived by the sense of hearing is based on variations in air pressure and motion; at a temperature of 20° Centigrade it moves through the air at a speed of 343.8 meters per second. This is the **moving sound wave**. If the pressure impulses follow each other at regular intervals, a tone is produced, the pitch of which is in relation to the frequency of the impulses. The normal tone **a'**, to which orchestral instruments are tuned, has 440 vibrations per second; the distance of 343.8 meters traversed during this unit of time contains 440 sound waves. The basic acoustical rule of free air states that the length of a wave multiplied by the frequency gives the speed of sound.

In acoustics, one differentiates between the moving sound wave, described above, and the **standing sound wave**. According to the current conception, it originates in the superposition of sound waves of the same frequency traveling in different directions. It is distinguished by air particles performing a stationary vibration in their place in the same phase. That is to say, they are always to be found at the same time in a median or terminal position. The amplitude of a vibration decreases from its maximum at the antinode to its minimal point at the node. During vibration, every particle receives a changing pressure from its neighbor, provoking acceleration or deceleration, respec-

tively. The pressure forces accumulate in the horizontal axis of the sound wave until the next vibration node, where they exert the maximum variation in pressure. There are pressure variations at every point of the sound wave. These are called sound pressure. Sound pressure is at its greatest in the vibration nodes, for which reason these places are also called pressure loops.

A. Acoustical measurements of a horn

Sound pressure and its fluctuation can be measured with a microphone, passed through the proper electrical equipment, and registered on a moving strip of paper as a curve.

Fig. 1 shows the development of sound pressure in the horizontal axis of an F horn (8th tone of the harmonic series). The arcade-like curve displays 8 maxima, where the vibration nodes are found. In the downward-oriented points are found the pressure minima or vibration loops. The distance between two neighboring minima corresponds to half a sound wave. This distance taken twice and multiplied by the frequency gives a number differing from the speed of sound. This number is always inscribed between two points on the abscissa. We will return to this deviation in **Figure 4**.

The sound pressure curve in **Figure 1** shows a vibration node K^1 where the lips touch the mouthpiece, and a vibration loop B^8 at an indeterminate point within the bell. If a (non-transposing) mute is inserted in the bell, a minimum pressure point (vibration loop) appears with the dashed curve, and following this the sound pressure in the bottom of the mute rises again until the maximum K^9 .

In **Fig. 2** these two curves are supplemented by a line in dots and dashes representing the course of the sound pressure with complete stopping. A maximum pressure point is formed in the palm of the hand at a distance of Δ^1 from the maximum pressure point in the bottom of the mute, and shifted in the direction of the mouthpiece. The acoustical length of the horn is shortened by this distance, for which reason the pitch rises. With the F horn, this pitch rise corresponds to about half a tone. The second valve lengthens the horn, in its turn, by the same amount, so that the pitch of the open horn is sounded. When the horn is stopped completely, its tonal character is changed; it is soft, muted like an echo. Incomplete hand stopping, by means of which the pitch is lowered, causes a lengthening of the vibrating air column.

Fig. 3 shows the position of the vibration loops in the axis of the horn for the 2nd through 12th notes of the harmonic series, designated by tiny circles. The product of the double distance of two neighboring vibration loops and the frequency gives a number which increases from the mouthpiece to the bell end. In **Fig. 4** these numbers are given in their corresponding distances from the mouthpiece. The measurements from **Figure 1** are shown as x's. A curve has been drawn through the forest of points. For purposes of comparison a line, in dashes, shows the speed of sound in free air. The difference between the ascending curve — the product of twice the distance of two neighboring vibration loops and the frequency — and the horizontal line, representing the speed of sound in free air, has not yet been physically explained.

B. Commentary for the hornist

In order to render the physico-acoustical phenomena more accessible to the practical musician, we wish to emphasize the most important processes in the following remarks, whereby some of the preceding findings will be repeated.

The discovery of the Dresden hornist Josef Hampel, around 1750, according to which the hand lowers the tone when it is partially inserted into the bell and raises the pitch by half a tone when it stops the bell completely, had a revolutionary effect on composers' treatment of the horn. Through his discovery, it became possible to employ the horn chromatically instead of remaining restricted to the notes of the harmonic series. Of course, there was a price to be paid in the radical change of tone color of the stopped tones. The phenomenon of the change of pitch remained unexplained up to the present day. Morley Pegge writes in his excellent book, **The French Horn** (London 1960), p. 132: «For all their laboratory paraphernalia none of the acousticians has offered a convincing explanation of the rise of pitch that occurs when we «stop» a note». Our experiments have brought the physical explanation of the phenomenon, 220 years after its discovery.

In **Fig. 2** the sound pressure curves show us three different vibratory situations.

1. With an open horn, the air particles in the end of the bell vibrate with maximal vibration amplitude and minimal sound pressure; we speak of a vibration loop or a pressure node. The sound wave is reflected here by a vibration which is termed a soft reflection. The course of the pressure is presented in Figure 2 by a drawn-out line. At an indeterminate point in the bell opening, the sound pressure falls off completely.

2. With a properly proportioned mute, pitch is not affected. In comparison with the curve of the open tones (normal line), the sound pressure curve of the muted tones (dashed line) shows a minimal pressure point in the bell, just as it does at various points within the horn itself, after which the pressure increases to a maximal point at the bottom of the mute. The bottom of the mute acts like a wall at which the air particles cannot vibrate; they undergo maximal pressure variation (pressure loop or vibration node), and the sound wave is reflected at this point in a hard reflection back into the horn. The position of the standing waves inside the horn is the same with a muted tone as with an open tone.

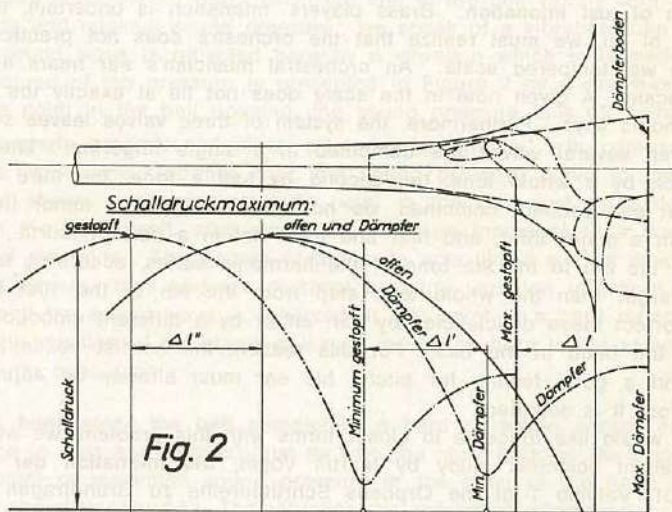
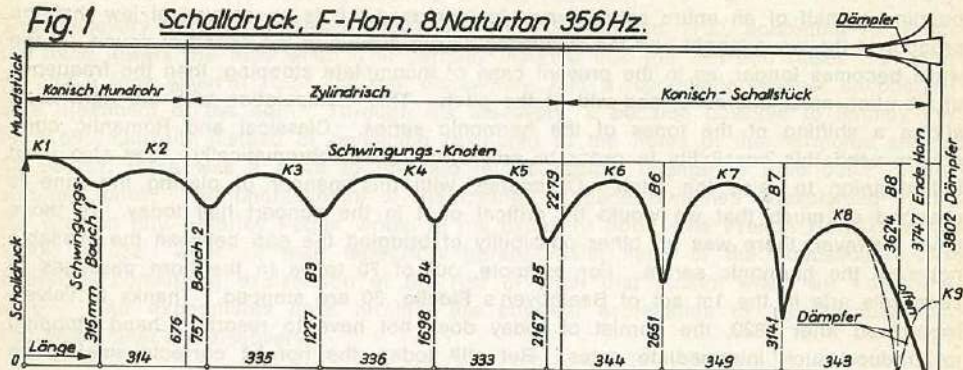
3. When the hand stops the bell completely, a hard reflection occurs on the palm of the hand (line in dots and dashes), just as with the mute bottom. As opposed to muted tones, the point of maximum sound pressure in the palm of the hand is shifted into the horn by the distance Δ^1 . The vibration air column is shortened by this distance, resulting in a corresponding rise in pitch. With an F horn, this pitch rise is equal to half a tone. When the second valve is depressed, the vibrating air column is lengthened by amount Δ^1 , resulting in the original pitch of the open or muted horn. The stopped tone sounds like an echo. Composers are fond of this effect. On the F horn, a stopped passage with echo effect must be transposed half a tone lower, to E horn. If a mute is used, the pitch remains of course the same as with the open horn.

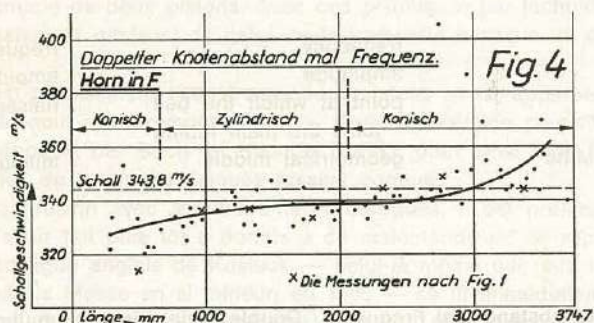
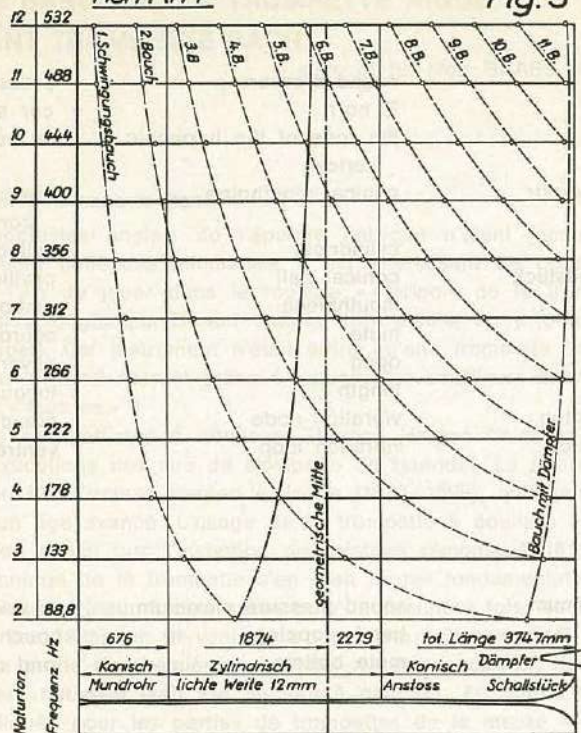
4. Besides these three situations, the hornist has the possibility of introducing his hand only partially into the bell, resulting in a pitch drop up to a full tone. The physical explanation of this is that the widening of the bell is cancelled out by the hand, thus lengthening the tubing. The distance between two neighboring vibration loops, corresponding to half of an entire sound wave, is increased. It is an acoustical law that the product of the wave length and the frequency always results in the speed of sound. If the wave becomes longer, as in the present case of incomplete stopping, then the frequency of vibration must decrease, and with it the pitch. This manipulation with the right hand allows a shifting of the tones of the harmonic series. Classical and Romantic composers used this possibility in order to employ the horn chromatically; they also used full stopping to raise the pitch. Of course, with this manner of playing the tone is changed so much that we would be critical of it in the concert hall today. In those days, however, there was no other possibility of bridging the gap between the available notes of the harmonic series. For example, out of 70 tones in the horn passages of Leonore's aria in the 1st act of Beethoven's **Fidelio**, 30 are stopped. Thanks to valves, introduced after 1820, the hornist of today does not have to resort to hand stopping to produce such intermediate notes. But still today, the hornist corrects small pitch differences with his hand. He can also influence pitch by changes of lip tension.

5. The problem of just intonation. Brass players' intonation is uncertain, and for two reasons. First of all, we must realize that the orchestra does not practice the compromise of the well-tempered scale. An orchestral musician's ear hears according to the harmonic scale. A given note in the scale does not lie at exactly the same pitch in various harmonic keys. Furthermore, the system of three valves leaves something to be desired when several valves are combined in a single fingering. The first valve lowers the pitch by a whole tone, the second by half a tone, the third by a minor third. The first and second, combined, do not quite result in a minor third, second and third not in a major third, and first and third not in a perfect fourth. The whole tone step from the 8th to the 9th tone of the harmonic series, according to the vibratory ratio, is larger than the whole tone step from the 9th to the 10th tones. The hornist must correct these deficiencies by ear, either by a different embouchure setting or by shift of the hand in the bell. For this reason, the hornist needs a fine-tuned musical ear and a good feeling for pitch: his ear must already be adjusted to the exact pitch before it is sounded.

For those who would like to come to closer terms with this problem, we would recommend the excellent scientific study by Martin Vogel, **Die Intonation der Blechbläser** (Düsseldorf 1961. Volume 1 of the Orpheus Schriftenreihe zu Grundfragen der Musik. Edited by the Gesellschaft zur Förderung der systematischen Musikwissenschaft).

Fig. 1 Schalldruck, F-Horn, 8. Naturton 356 Hz.





Traduction des termes / Traduction :
 Voir page suivante, glossaire
 See next page, glossary

Glossar

Glossary

Glossaire

FIGUR 1

Schalldruck	sound pressure	pression du son
F-Horn	F horn	cor en fa
8. Naturton	8th tone of the harmonic series	8e harmonique
konisches Mundrohr	conical mouthpipe	branche d'embouchure conique
zylindrisch	cylindrical	cylindrique
konisches Schallstück	conical bell	pavillon conique
Mundstück	mouthpiece	embouchure
Dämpfer	mute	sourdine
offen	open	ouvert
Länge	length	longueur
Schwingungsknoten	vibration node	nœud de vibration
Schwingungsbauch	vibration loop	ventre de vibration

FIGUR 2

Schalldruckmaximum	sound pressure maximum	pression de son maximale
gestopft	hand stopping	bouché
Dämpferboden	mute bottom	fond de sourdine

FIGUR 3

Frequenz	frequency	fréquence
lichte Weite	amplitude	amplitude
Anstoss	point at which the bell joins the main tubing	naissance du pavillon
geometrische Mitte	geometrical middle	milieu géométrique

FIGUR 4

Doppelter Knotenabstand mal Frequenz / Double nodal distance multiplied by frequency /
Double distance nodale multipliée par la fréquence.

Schallgeschwindigkeit	velocity of sound	vitesse du son
Messung nach	measures from	mesures d'après